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Research article

Equilibrium approach towards water resource management and pollution control in coal chemical industrial park

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ABSTRACT

In this study, an integrated water and waste load allocation model is proposed to assist decision makers in better understanding the trade-offs between economic growth, resource utilization, and environmental protection of coal chemical industries which characteristically have high water consumption and pollution. In the decision framework, decision makers in a same park, each of whom have different goals and preferences, work together to seek a collective benefit. Similar to a Stackelberg-Nash game, the proposed approach illuminates the decision making interrelationships and involves in the conflict coordination between the park authority and the individual coal chemical company stockholders. In the proposed method, to response to climate change and other uncertainties, a risk assessment tool, Conditional Value-at-Risk (CVaR) and uncertainties through reflecting parameters and coefficients using probability and fuzzy set theory are integrated in the modeling process. Then a case study from Yuheng coal chemical park is presented to demonstrate the practicality and efficiency of the optimization model. To reasonable search the potential consequences of different responses to water and waste load allocation strategies, a number of scenario results considering environmental uncertainty and decision maker' attitudes are examined to explore the tradeoffs between economic development and environmental protection and decision makers' objectives. The results are helpful for decision/police makers to adjust current strategies adapting for current changes. Based on the scenario analyses and discussion, some propositions and operational policies are given and sensitive adaptation strategies are presented to support the efficient, balanced and sustainable development of coal chemical industrial parks.

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1. Introduction

With the expansion of coal related industries, these water-intensive projects were constructed predominantly in arid western areas over the duration of the 12th Five-Year Plan (2011–2015) of China which will inevitably trigger a serious water crisis and exacerbate existing water scarcity problems (Li and Hu, 2017). Coal chemical industries are not only extremely water-intensive but also characterized by significant pollution with a large amounts of waste water directly into the river (Kavouridis and Koukouzas, 2008). The situation of severe water shortages, water pollution, and environmental degradation in coal chemical industrial areas has become increasingly serious and caused a major bottleneck in constraining sustainable economic and environmental development (Xie et al., 2010). Motivated by the conflicts between energy economy development and water resources and environmental protection, this paper aiming to improve the water utilization efficiency and minimize the industry's environmental impact and stresses the importance of regulated water resource allocation and pollution control strategy.

Nowadays, access to clean, affordable, reliable energy has been a cornerstone of the world's increasing prosperity and economic growth (Chu and Majumdar, 2012). With the development of clean coal technology, modern coal chemical industry has rapidly developed which is mainly involved with the production of clean energy and substitutes from diesel oil, gasoline, etc (China's National Energy Administration, 2015). It has been prioritized in

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recent years as it is expected to play a critical role in the sustainable development of energy resources (Xie et al., 2010; Man et al., 2017). The water resource scarcity and pollution problem have restricted the development of the coal chemical industry due to the reverse distribution of coal and water which is a prominent feature of China's resource endowments (Rubiocastro et al., 2010; Han et al., 2015). To battle with high water consumption and pollution that accompanies rapid industrial growth, most optimization studies have been focused on optimizing water exchange network or clean technology (Xiong et al., 2017). However, the associated problems of extensive energy use, water resource inefficiency, and heavy pollution have not been integrated to solve effectively (Tanaka et al., 2017; Shen et al., 2017).

With their increased resource efficiency and cleaner, more environmentally friendly production processes, coal-based energy parks have been seen as an efficient method to improve coal chemical industry sustainability (Lin and Long, 2015; Yune et al., 2016). Evidence has shown that encouraging a symbiotic relationship between the coal chemical plants in the same industrial park can significantly contribute to the sustainable development of the industrial activities (Boix et al., 2015). Industrial parks, which are established based on IE, have a number of independent companies and have the aim of concentrating economic development and the associated environmental pollution into a geographically confined area Ren et al. (2016). Therefore, these eco-industrial parks (EIPs) present both opportunities and challenges for environmentally sustainable industrial development Shi et al. (2010). While the industrial concentration in the parks makes it possible to achieve the proposed Sustainable Development Goals (SDG) Griggs et al. (2013); UN (2016) and gain economic and environmental benefits, this symbiosis between the industrial activities could lead to pollution and resource depletions that exceed local environmental carrying capacities. By applying a new paradigm of principles and system tools, IE provide concrete guidance for industrial park decision support activities Edgington (1995); Pauliuk et al. (2017). IE, as a solution-driven approach, integrates the environmental concerns into the production and resource utilization strategies with research having suggested a variety of practical initiatives. Comprised with those study which focused on certain point of resource or environmental problem, there has been less attention paid to developing a systematic, comprehensive methodology for reducing pollution, water resource saving, and increasing economic effectiveness (Zhang et al., 2015; Xinchun et al., 2017).

Water use and environmental protection problems have often been resolved using water allocation or quality control superstructure-based model, where the water is optimally distributed, treated and discharged in a region (Lovelady and El-Halwagi, 2009; Xie et al., 2017). Integrating water resource management and environmental protection through water and waste load allocations has also been studied for water resource and environment management in a river basin (Wang and Huang, 2011; Zeng et al., 2017a). Few total pollution control management techniques have been integrated into water environmental management systems of a industrial park. Therefore, to address this research gap, in this paper, total pollution, quality control, and water resource efficient allocations are integrated in a systematic model, in which the decision framework incorporates both the management objectives of the individual companies and the balanced development of the park as a whole, and accounts for the conflicting objectives of the participants who prioritize individual clean production based on IE and the park authority who prefers to focus on the overall economic growth while maintaining or improving the park's environmental performance (Leong et al., 2017).

The park authority and the coal chemical company stakeholders who the have conflicting objectives and preferences as decision makers are participated in the water resource and environmental management of the park. Decisions are made sequentially from the upper level to the lower level, with each level decision makers having different powers of control over the management objectives and decisions. Therefore, this decision situation fits with a decentralized decision system in which one leader and several followers of equal status are involved (Liu, 1998). A powerful tool dealing with this decision systems is the so-called bi-level programming (Wen and Hsu, 1991; Anandalingam and Apprey, 1991). And the conflict between economically efficient growth and environmental protection, or the tension between the economic utility of the natural resources and their ecological utility in the natural environment, has not been completely solved under EIP development as excessive water consumption and high emissions necessitate a trade-off between economic development and environmental sustainability. In this problem, to coordinate the relationship between the economy and the environment, a multi-objective method which involve more than one objective function is applied to model the optimal water and waste load allocations for the entire industrial park (Xu et al., 2011, 2016b; Leong et al., 2017). The set of solutions gained from multi-objective optimization model define the best tradeoff between competing objectives that is more in line with the problems being studied. As the external uncertainties in this integrated water resource and waste load allocation optimization model could result in different water and waste allocation strategies, a risk evaluator of the conditional value at risk (CVaR) which are employed to assess the impacts of degrees of the preference of decision makers on the tradeoff between system benefits and expected economic losses (Wang et al., 2017). And probability and fuzzy set theory are used to deal with uncertainty parameters and variables. Scenarios are then examined to evaluate the uncertainties related external environmental change, and the decision maker' attitudes, and to develop sensitive adaptation strategies to mitigate environmental damage and adapt to possible climate conditions (Wu et al., 2017). Motivated by the contradictions between economic development, environmental protection, and climate-change mitigation in the coal chemical industrial park, this paper develops an equilibrium approach for efficient energy conservation, water utilization and pollution control based on IE (Tang et al., 2015; Niu et al., 2017).

2. Key problem statement

To improve the efficiency of energy conservation, water utilization, and ensure environmental protection, a decision making framework, as shown in Fig. 1, is developed aiming at collective benefits achievement with equilibrium water and waste load allocation strategies.

2.1. Coordinating economic and environmental conflicts based on IE

Significant environmental problems rose with rapid development of coal chemical industrial, particularly as the worsening environmental conditions have resulted in major challenges to economic growth (Chu and Majumdar, 2012). By incorporating multi-objective procedures into the decision making process, the park decision maker attempts to balance the economic and environmental goals so that the proposed model is more realistic and results in an ecological solution to coal chemical industrial operations. As a multi-objective optimization problem is able to search

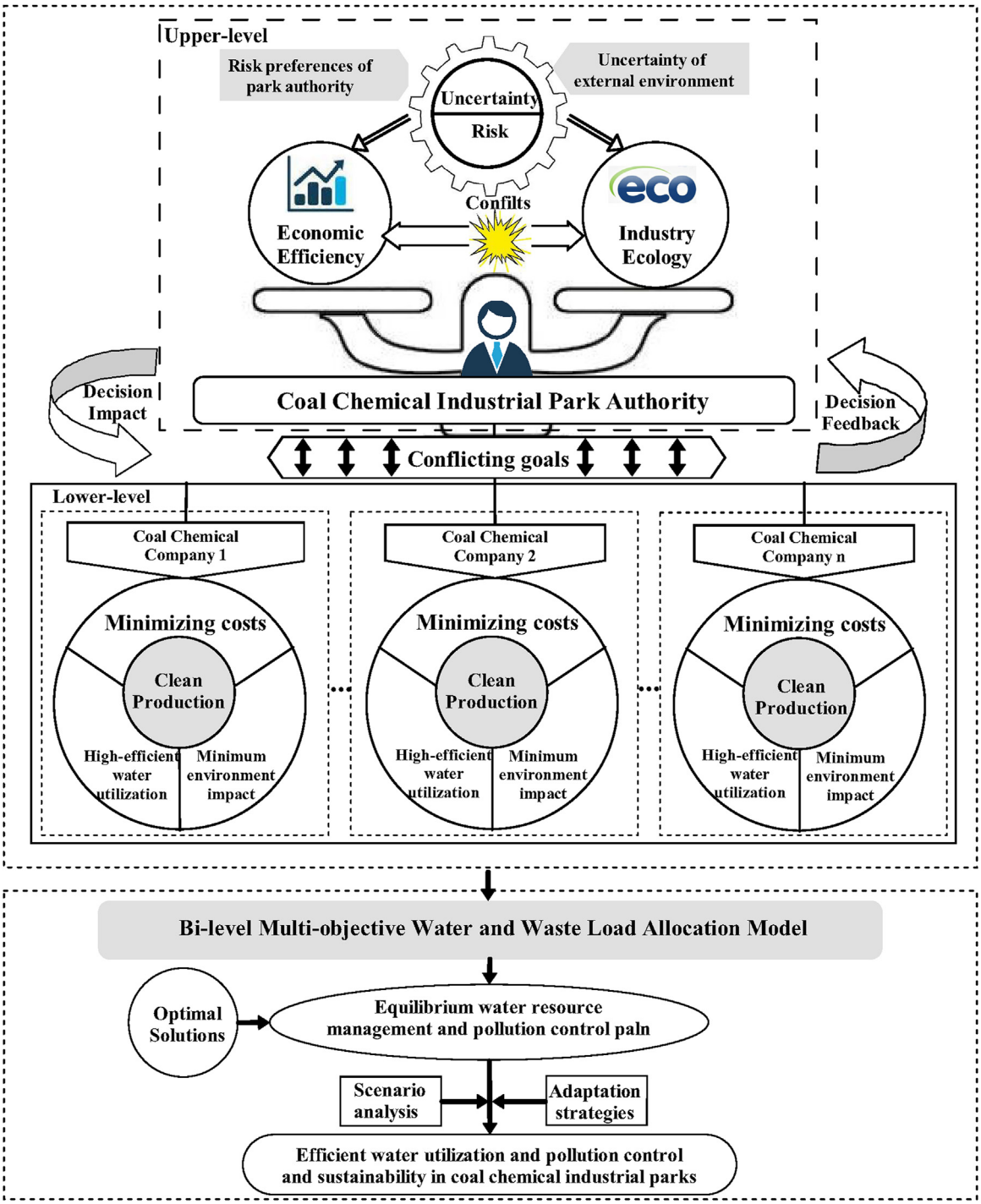

Fig. 1. Decision framework for water utilization and pollution control.

for trade-off solutions under various scenarios, a trade-off curve known as the Pareto front is generated, which provides a greater number of alternative strategies for decision or policy makers. A solution-driven approach is proposed through the design of appropriate resource utilization and production strategies to help minimize environmental damage while improving economic performance (Karn and Bauer, 2001), thereby resolving the conflicts between economic growth and environmental protection (Alper, 1992).

2.2. Seeking eco-industrial collective benefits and conflict trade-offs

In this problem, a group of decision-makers with conflicting interests develop an eco-industrial park under an IE framework (Shi et al., 2010). The park authority and private stakeholders work together to gain collective benefits rather than only optimizing each individual performance (Liu et al., 2015). In this paper, the different hierarchical decision making levels of the park authority/policy maker and the company stakeholders, each of which have

conflicting objectives, are integrated in the decision making system framework. The park authority is responsible for improving the economic performance of the park while minimizing the environmental impacts (Tian et al., 2014), and has the higher authority for managing the environmental, water and energy use issues, all of which can influence the performance of the individual stakeholders through the implementation of policy or incentive mechanisms. The participating companies are the followers who need to abide by the park authority's decisions but are able to individually embed IE based clean production and pollution prevention strategies in their industrial activities. The followers react to the leader's strategy and seek to develop collective optimal strategies. The decision making process between the park authority and the individual companies is therefore similar to a Stackelberg game (Stackelberg and Peacock, 1953; Stackelberg et al., 2011). It emphasizes trade-offs between two levels of objectives with the conflict between these stakeholders finally arriving at a Stackelberg-Nash equilibrium (Nash, 1951). The solution to the bi-level water and waste load allocation optimization problem is the Stackelberg-Nash equilibrium (Liu, 1998) that can achieve collective benefits for the entire eco-industrial park.

2.3. Adaptation strategies for environmental changes

A systematic decision making framework is designed to support efficient water use and pollution control and respond to environmental changes with the aim of achieving sustainable development. As eco-industrial park water supplies are usually taken from rivers, groundwater or recycled water resources, with the capacity of the water bodies depending on many meteorological and hydrological factors, there are many uncertain features (Walther et al., 2002), such as changes in rainfall, all of which can impact the quality and quantity of water resources available to the industrial ecosystem (Xu et al., 2013, 2015b). To cope with these extensive water resource and water environment system uncertainties, probability and fuzzy set theory are used to deal with the probabilistic and discrete interval uncertainties in water and waste load allocation problems. Available water fluctuations are the main water resource allocation uncertainties, as these directly affect industrial production, thereby causing economic efficiency loss risks (Kong et al., 2017). This is especially evident in the coal chemical industries which have high water and energy consumption and high pollution (Hu et al., 2016; Zhuang et al., 2017). In this paper, the conditional value at risk (CVaR) is used as the risk evaluator to measure the economic losses across the entire coal chemical park in various scenarios to assess the adverse impact of environmental changes on the delivery of ecosystem services. Uncertain parameters, such as water flow can be expressed as a probability distribution; however, as the other uncertain factors cannot be expressed as probability density functions (PDFs) due to the lack of available monitoring data, fuzzy sets can be used to identify effective water resource and pollution management alternatives (Poff et al., 2016; Zeng et al., 2017b). Therefore, based on the sustainability insights gained from IE, to respond to the environmental changes, this paper develops adaptation strategies through various scenarios to support improvements in the economic and environmental performances of both the individual park companies and the park as a whole.

3. Modeling

The mathematical description of the above conceptual model and an efficient solution approach is presented in this section.

Index	
i	Index for coal chemical companies located in the same industrial park
j	Index for coal chemical projects
t	Index for target control pollutants
Decision variables	
Y_i^f	Freshwater allocated to company i
Y_i^w	Waste load for pollutant t allocated to company i
x_{ij}^f	Allowable water consumption for the jth coal chemical project production at company i
x_{ij}^w	Allowable water waste discharge of the jth coal chemical product production at company i
Certain Parameters	
sc_i	Unit removed costs for the pollutants
$E(t)$	Current emissions of pollutant t
τ	Pollution tax per unit of pollutant t
$R(t)$	Emissions reduction rate for pollutant t
UR_i	Unit costs for wastewater reuse in company i
$C^s(t)$	Standard effluent concentration of pollutant t
PC_{ij}	Production capacity for project j at company i
PD_{ij}	Minimum yield demand for project j at company i
b^{max}	Maximum economic return per unit of water consumption
b_i	Industrial output value per unit of water consumption at company i
r_i	Pollutant removal rate through the sewage treatment facilities
WD_i^{min}	Minimum water resource demand to maintain production at company i
v	Equivalent value for the different pollutants that measures the environmental harm
Uncertain Parameters	
$\widetilde{\mu}_i$	Water recycling rate inside the company i
$\widetilde{\gamma}_i$	Wastewater discharge coefficient at company i
$\widetilde{\rho}_i^{loss}$	Water transfer loss ratio from supply centre to company i
$\widetilde{ue}_{ij}$	Unit operating costs for the jth coal chemical project at company i
$\widetilde{uc}_{ij}$	Unit water consumption for the jth chemical project production at company i
$\tilde{Q}$	Uncertainty of available water resources from the external environment
Risk attitude parameters	
α	Park authority's risk-aversion degree
ε	Park authority's tolerance level for economic efficiency loss

3.1. Assumptions

Before establishing the model in this paper, the following model assumptions are outlined:

1. Water and waste load allocation period is set as one year. Before the next plan cycle begins, a new water resource and environmental management plan is developed under the scenario at that time.
2. The lower-level decision makers, coal chemical companies, are able to receive water from only two sources (i.e., fresh and re-generated water).
3. The operating costs of a coal chemical project is assumed including capital costs, energy costs, and water consumption costs.
4. The main pollutants, chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N), are as the control factors to evaluate the environmental damage in this paper.

3.2. Model development

This section describes the development of the proposed bi-level multi-objective mathematical model.

3.2.1. Coordinating overall economic and environmental park performance

To determine the economically and environmentally optimal status for the industrial ecosystem, the park authority has to trade off efficient economic growth and environmental protection. Based on IE theory, the objectives of the decision maker, therefore, are to

minimize the economic efficiency loss risks while minimizing total pollution to reduce environmental damage.

Minimizing total pollution

Pollutants emitted from the coal conservation process can cause direct or indirect environmental damage. While some treatment technologies can reduce the emissions, they are unable to radically control environmental pollution damage. To control environmental pollution, previous studies have sought to implement total water pollutant control programs through the setting of effluent standards (Jia et al., 2016).

However, it is more efficient to develop integrated control strategies rather than develop separate strategies for each individual pollutant. As there are many pollutants produced as a result of the coal chemical production process, the park authority needs to implement controls to minimize the total environmental impact.

$$F_1 = \sum_{t=1}^{T}\sum_{i=1}^{m} Y_i^w(t)v(t) \tag{1}$$

where $Y_i^w(t)$ is the waste load of pollutant t allocated to company i, and $v(t)$ refers to the equivalent value of the different pollutants based on their degree of harm to the environment and technical treatment economics (People, 2008).

Economic efficiency loss risk aversion objective

As the high water consumption needs of the coal chemical industries can aggravate fresh water scarcity and further affect economic safety, CVaR is developed to coherently measure the expected economic losses as the actual losses exceed the Value at Risk (VaR) threshold (Moghaddam et al., 2013). Based on known probability distributions of random variables, CVaR is designed to measure and quantify the level of the likelihood of incurring losses caused by water resource shortage. Since the scope of risk assessed is limited and the tail end of the distribution of loss is not typically assessed, if losses are incurred, the amount of the losses will be substantial in value.

The objective is to estimate the economic efficiency for a prescribed probability level. Let $L[(Y_i^f, \tilde{Q})]$ be the risk-averse economic efficiency measure for the park authority that is associated with the water allocation volume Y_i^f decision variable at the *ith* coal chemical company. The park economic efficiency is defined as the coal chemical production economic returns divided by the maximum potential economic returns under uncertain water resource flows.

$$L\left(Y_i^f, \tilde{Q}\right) = 1 - \frac{\sum_{i=1}^{m} b_i\left(1 - E\left[\widetilde{\gamma_i^{loss}}\right]\right)Y_i^f}{b^{max}\left(\tilde{Q} + \sum_{j=1}^{m}\sum_{j=1}^{n}\lambda_i E\left[\widetilde{\beta_i}\right]x_{ij}^f\right)}$$

where b_i is the industrial output value per water unit at company i and b^{max} is the maximum economic return per unit of water consumption in the coal chemical industry. The CVaR value at a specific confidence level $\alpha \subset [0, 1]$ can therefore be calculated as follows;

$$CVaR_\alpha = E\left\{L\left[\left(Y_i^f, \tilde{Q}\right)\right] \middle| \Psi\left(Y_i^f, \tilde{Q}\right) \geq \alpha\right\}$$

where the cumulative distribution function of loss at decision vector x is $\Psi(x, \xi) = Pr\{f(x, \xi) \geq \alpha\}$.

To ensure a mathematically well-behaved risk measure, $CVaR_\alpha$ can be expressed using the following linear minimization formula, which minimizes the following linear function over both α and the decision variable x that $CVaR_\alpha$ has been shown to be equivalent to the following model (Rockafellar and Uryasev, 2010):

$$CVaR_\alpha = min\, F_\alpha(x, \zeta_\alpha) = \zeta_\alpha + \frac{1}{1-\alpha}\sum_{s=1}^{M} P_s\left[-L\left[\left(Y_i^f, \tilde{Q}\right)\right] + \zeta_\alpha\right]^+ \tag{2}$$

where $\zeta_\alpha(Y_i^f)$ is the VaR value that represents the maximum loss at a specific confidence level α, α represents the park authority risk-aversion degree, the smaller the α, the more risk-averse; and 1-α denotes the accumulated probability that the water use economic efficiency losses are lower than $\zeta_\alpha(Y_i^f)$.

(1) Water resource availability constraints

$$\sum_{i=1}^{m} Y_i^f \leq \tilde{Q} + \sum_{i=1}^{m}\sum_{j=1}^{n}\lambda_i E\left[\widetilde{\beta_i}\right]x_{ij}^f \tag{3}$$

where $\tilde{Q}$ is the uncertainty of available water resource from the river flow and $\sum_{i=1}^{m}\sum_{j=1}^{n} E[\widetilde{\beta_i}]x_{ij}^f$ is the wastewater produced in the park, in which $\widetilde{\beta_i}$ is the wastewater discharge coefficient, which because of the influence of various objective factors can not be exactly valued; however it can be estimated and as using typical triangular fuzzy numbers, with the most likely value being in a relatively smaller range. Based on fuzzy set theory, $\widetilde{\beta_i}$ can be described as $\widetilde{\beta_i} = (k_{i1}, k_{i2}, k_{i3})$ with a most possible value of k_{i2} and the lower and upper bounds, k_{i1} and k_{i3}. However, this parameter can not be directly calculated, in this paper, the expected value operator method for fuzzy numbers proposed by (Xu and Zhou, 2012) is used. To efficiently utilize the limited fresh water resources and reduce the wastewater discharges that can cause water environment pollution damage, as much water as possible should be recycled; therefore, λ represents the wastewater reuse rate, which depends on the overall plan for reducing water consumption across the park.

(2) Water consumption constraint

The supplied water should be larger than the minimized fresh water demand:

$$WD_i^{min} \leq \left(1 - E\left[\widetilde{\gamma_i^{loss}}\right]\right)Y_i^f$$

where WD_i^{min} is the minimum water required to maintain production at company i. γ_i is the water loss coefficient due to evaporation, leakage, drainage piping and other losses in the coal conservation and effluent processes, and $E[\widetilde{\gamma_i^{loss}}]$ is the expected value of the water transfer loss ratio from the supply centre to company i.

(3) Pollution emissions reduction requirements

To balance the relationship between economic development and environmental protection, total pollutant emissions should not exceed the load capacity of the external environment; therefore, the park authority must ensure a low level of total pollutant discharge;

$$\sum_{i=1}^{m} Y_i^w \leq (1 - R(t))E(t), \quad \forall\ t$$

where $E(t)$ is the current pollutant emissions, with $R(t)$ being the planned pollutant emissions reductions over the year.

3.2.2. Cost-effective clean production for the individual park companies

Under the ecological policy requirements, each coal chemical company must implement environmental protection facilities construction to reduce environmental damage (Service, 2017). Therefore, the effect on production costs of the environmental tax payments (Xie et al., 2010), and any increase in coal prices cannot be ignored. Minimizing clean production costs must therefore account for unit operation costs, wastewater reuse costs, and the pollution tax;

$$TC_i = \sum_{j=1}^{n} E\left[\widetilde{ue_{ij}}\right] \frac{x_{ij}^f}{E\left[\widetilde{uc_{ij}}\right]} + UR_i\lambda_i \sum_{j=1}^{n} E\left[\widetilde{\beta}_i\right] x_{ij}^f + \sum_{t=1}^{T}\sum_{j=1}^{n} v(t)[\times (sc_i r_i(t) + \tau(t)(1 - r_i(t))]x_{ij}^w(t) \quad (4)$$

where ue_{ij} is the unit energy costs for the production of a unit of the j chemical product at company i, $E[\widetilde{ue_{ij}}]$ is the expected value of the trapezoidal fuzzy number $\widetilde{ue_{ij}}$, $E[\widetilde{uc_{ij}}]$ is the expected water consumption per unit for the j chemical production project at company i. UR_i is the wastewater recycling costs and $r_i(t)$ is the reused wastewater percentage. For the total pollutants produced by all park industrial activities, r_i of them are removed in the sewage treatment facilities with an expected unit removed cost of sc_i for coal chemical plant i. Let τ be the unit pollutant tax per pollutant t unit that coal chemical company i must pay $\sum_{t=1}^{T}\sum_{j=1}^{n} v(t)[\tau(t)(1 - r_i(t))]x_{ij}^w(t)$ for the damage to the environment.

Each plant in the park develops clean production plans to minimize total costs under the water and pollutant discharge rights allocated by the park authority. Then, the park coal chemical companies decide on individual water and waste load allocation strategies to support clean-efficient production, which are then fed back to the upper level decision system. Therefore, as mentioned, the park authority' goals are impacted by Stackelberg game theory (Xu et al., 2016a; Yao et al., 2016).

(1) Available water resource constraint

The total water resources allocated to all park coal chemical projects cannot exceed the available water rights issued by the park authority.

$$\sum_{j=1}^{n} x_{ij}^f \le \left(1 - E\left[\widetilde{\gamma}_i\right]\right) Y_i^f$$

(2) Pollutant emissions constraints

To reduce the water environment damage, total pollution control is the priority of IE target. As pollution discharge rights are assigned to each park company, the waste load allocations clearly identify the pollutant discharges permitted for each production project.

$$\sum_{j=1}^{n} x_{ij}^w \le Y_i^w$$

(3) Water quality constraints

As an important tool in water environment management, water quality controls can provide a reasonable guide to the sewage discharged into the external water environment. The more control imposed on water quality, the lower the risk of unforeseen pollution emergencies.

$$\frac{\sum_{j=1}^{n}(1 - r_i(t))x_{ij}^w(t)}{(1 - \mu_i)\sum_{j=1}^{n} E\left[\widetilde{\beta}_i\right] x_{ij}^f} \le C^s(t)$$

The total pollutants discharged to water environment that not included the removed pollutants by treatment facilities are $\sum_{j=1}^{n}(1 - r_i(t))x_{ij}^w(t)$. And the wastewater could be pumped into the river system is $(1 - E\mu_i)\sum_{j=1}^{n} E[\widetilde{\beta}_i]x_{ij}^f$ with a recycling rate μ_i within the company. Where $C^s(t)$ is the emission standard for pollutant t based on the water quality standards.

(4) Product yield constraints

Each coal chemical project produces products to meet the minimum market demand under the production capacity constraints imposed by the water resource,

$$PD_{ij}^{min} \le \frac{x_{ij}^f}{E\left[\widetilde{uc_{ij}}\right]} \le PC_{ij}$$

where uc_{ij} is the water demand per unit of coal chemical product i produced at company i, and PC_{ij} is the production capacity of product j at company i.

3.2.3. Global model

Guided by the IE principles, a bi-level multi-objective water and waste load allocation model is established, as the global model showed in Eq. (5), to achieve efficient water utilization and reduce environmental damage (Jia et al., 2016). Each individual coal chemical company can achieve cleaner production and pollution reductions through the integration of IE tools and approaches. In coal chemical industrial parks where all participants share the same eco and industrial systems, the park authority and the individual stakeholders work collectively in an integrated system to achieve higher benefits than can be achieved individually (Grafton et al., 2013). As this model is focused on an eco-industrial park, it not only aims to coordinate the conflicts between economic development and environmental protection, but also seeks to resolve the conflicting objectives between the park authority on the upper level and the company stakeholders on the lower level. As the leader, through the water resource and pollutant emission rights allocations, the park authority seeks to minimize water pollution emissions with minimum economic efficiency loss risk, and based on these water and waste load allocations, the individual park stockholders develop IE based production plans to improve their individual water use efficiency and minimize costs through the reallocation of the water resources and waste loads to different coal chemical projects. The park authority and park companies optimize their objective functions without considering the other partys objectives; however, the decisions of each party affect both the achievement of these individual objectives and their decision space. The Stackelberg game between the two levels of decision makers allows for a trade-off between the ecological and industrial systems (Boix et al., 2015). Through an energy and resource utilization and environmental protection synthesis in the decision making framework, the proposed model provides a promising strategy to reconcile conflicts between economic growth and environmental protection and objective conflicts of decision makers (Edgington, 1995).

$$\min F_1 = \sum_{t=1}^{T}\sum_{i=1}^{m} Y_i^w(t)v(t)$$

$$\min F_2 = \zeta_\alpha + \frac{1}{1-\alpha}\sum_{s=1}^{M} P_s\left[L\left(Y_i^f, \tilde{Q}\right) - \zeta_\alpha\right]^+$$

s.t.

$$\begin{cases} L\left(Y_i^f, \tilde{Q}\right) = 1 - \dfrac{\sum_{i=1}^{m} b_i\left(1 - E\left[\widetilde{\gamma_i^{loss}}\right]\right)Y_i^f}{b^{max}\left(\tilde{Q} + \lambda\sum_{i=1}^{m}\sum_{j=1}^{n} E\left[\tilde{\beta}_i\right]x_{ij}^f\right)} \\ \sum_{i=1}^{m} Y_i^f \le \tilde{Q} + \lambda\sum_{i=1}^{m}\sum_{j=1}^{n}\beta_i x_{ij}^f \\ WD_i^{min} \le \left(1 - E\left[\widetilde{\gamma_i^{loss}}\right]\right)Y_i^f \\ \sum_{i=1}^{m} Y_i^w \le (1 - R(t))E(t), \quad \forall\ t \\ Y_i^f \ge 0 \quad Y_i^w(t) \ge 0 \\ \min TC_i = \sum_{j=1}^{n} E\left[\widetilde{ue_{ij}}\right]\dfrac{x_{ij}^f}{E\left[\widetilde{uc_{ij}}\right]} + UR_i\lambda_i\sum_{j=1}^{n} E\left[\tilde{\beta}_i\right]x_{ij}^f \\ + \sum_{t=1}^{T}\sum_{j=1}^{n} v(t)[(sc_i r_i(t) + \tau(t)(1 - r_i(t))]x_{ij}^w(t) \\ \text{s.t.} \\ \sum_{j=1}^{n} x_{ij}^f \le \left(1 - E\left[\widetilde{\gamma_i^{loss}}\right]\right)Y_i^f \\ \sum_{j=1}^{n} x_{ij}^w \le Y_i^w \\ \dfrac{\sum_{j=1}^{n}(1 - r_i(t))x_{ij}^w(t)}{(1-\mu_i)\sum_{j=1}^{n} E\left[\tilde{\beta}_i\right]x_{ij}^f} \le C^s(t) \\ D_{ij}^{min} \le \dfrac{x_{ij}^f}{E\left[\widetilde{uc_{ij}}\right]} \le PC_{ij} \\ x_{ij}^f \ge 0 \quad x_{ij}^f \ge 0 \end{cases} \tag{5}$$

The solution-driven IE approach coordinates the conflicts between economic performance and environmental sustainability by addressing the conflicting objectives of the decision makers on the two levels (Liu et al., 2015), and providing water resource and environmental management system equilibrium strategies (Xu et al., 2015a). The proposed model mathematically deals with both the bi-level conflicts and the multi-objectives to suggest sustainability solutions for any future water environment changes through the application of CVaR risk measurement technology and probability and fuzzy set theory to tackle the uncertain parameters. Sensitive adaptation strategies are then developed through various scenarios based on the solution-driven approach presented in this section that respond to the environmental changes impacting the industrial ecosystem. The model can be applied to similar situations by adjusting the policy control parameters or by changing, adding or removing the park authority objective functions for the constraints to address complex systems integration and identify effective solutions to sustainability challenges.

3.3. Model solution approach

The water and waste load allocation programming model with a single decision maker, the park authority, on the upper level, and multiple individual coal chemical company decision makers on the lower level is shown in Eq. (5). In the bi-level model, the water resource and waste load decision variables are divided into two subsets, one of which is controlled by the leader (Y_i^f and $Y_i^w(t)$) and the other of which is controlled by the followers (x_{ij}^f and x_{ij}^f). The followers resolve the inner problem to optimize total costs (Eq. (4)). The leader then examines each followers' feasible choice x_{ij}^f and x_{ij}^f, with the feasible region of the upper level optimization problem being determined by the leader's own constraints as well as the inner optimization problem (Sinha and Sinha, 2007). As this problem is a nonconvex problem and therefore complicated to solve (Saharidis and Ierapetritou, 2009), in this paper, a Karush-Kuhn-Tucker (KKT) transformation method, which is a decision-making process from a lower to higher level, is applied. The KKT optimal conditions are incorporated into the lower level programming cost minimization objective (Eq. (4)) and the resource and production capacity constraints. By employing the Lagrange multipliers on the constraints, as shown in Supplementary Material, the problem is transformed into an equivalent (one-level) mathematical program under appropriate constraints.

On the upper level, the park authority must simultaneously handle multiple conflicting goals to achieve economic benefits and minimize environmental damage. As these economic and environmental goals are expressed in different measurement units, the integration of the various goal-deviations in their original forms has no practical significance in Eqs. (1) and (2). To overcome these differences, this paper implements a ε-constraint method for producing the Pareto optimal solutions for the multi-objective planning model. The multi-objective optimization problem is then transformed to an IE based single-objective optimization problem (Qi and Jiang, 1997) with the objective being expressed in Eq. (1) and the additional constraints being expressed in Eq. (2) using a constraint vector ε. A bi-level model is very similar to a multi-objective problem as they both have conflicting objectives. In the transformed model, optimum computing solutions can achieve equilibrium for the various decision makers and trade-off the conflicting objectives. Therefore, in this paper, ε-constraint method and the KKT method are integrated to solve the proposed model.

4. Case study

In this section, the Yuheng coal chemical industry park is taken as a case study to demonstrate that practicality of the proposed model.

4.1. Study area

The Yuheng coal chemical industry park is located in Yulin City on the Northern Shaanxi Loess Plateau and Mu Us Desert border area in China. While the area has large reserves of good quality coal, it has poor water resources, with the per capita water resources being only 865 m^3 which is far below the provincial and the national averages. As one of the "two parks and six districts" in Yulin's energy development plan, the Yuheng coal chemical industrial park has a total planned area of 48.5 km^2, as shown in Fig. 2. Five large state-owned energy and chemical companies with varying projects are located in the Yuheng coal chemical industrial park. The main water supply comes from the Wang Gedu reservoir located upstream of the Wuding river. The Wang Gedu reservoir water transport project report claimed that the reservoir can guarantee 155 million m^3 of water to the park industrial area every year. However, according to the Overall plan for the Shaanxi Yuheng Coal Chemical Industry Park (2010–2030), the current water consumption demand by the park industries is higher than supply; therefore, it has become urgent to address this water scarcity problem. With the accelerated pace of industrial construction in the park, besides the water shortage problems, there are also issues with poor quality water. Therefore, as this conflict between continued industrial development, limited water supplies, and environmental pollution could severely restrict future park development, to ensure the stable, clean, sustainable development of the industrial park, it is necessary to devise a strategy that efficiently utilizes the water resources and effectively controls pollution.

4.2. Data collection

The data were taken from the "Report on the Environmental Impact Assessment of the Development Plan for the Yuheng Industrial Zone" (Yulin High-tech Industrial Development Zone Management Committee, 2017) and regional public information and statistical yearbooks. From the "Overall plan for the Shaanxi Yuheng Coal Chemical Industry Park (2010–2030)" and the "Yulin high-tech Zone 13th Five-Year Plan", sustainable development forecasts for the minimum freshwater demand for each company and the production capacities for each project were determined, as shown in Table 1.

The industrial park is in a dry region that has little rain and high evaporation. The surface water resources are small and the spatial and temporal distribution of the surface water runoff is uneven, which means that the water supply in this area is limited and uncertain. To define the stochastic parameters for the freshwater, scenarios and probability, mass functions based on Gaussian quadrature are used in the following steps (Miller and Rice, 1983); (1) based on historical data, the mean and coefficient of variation (CV) for the $\tilde{Q}$ are estimated; (2) it is assumed that $\tilde{Q}$ complies with a normal distribution, for which the expected value and standard deviation (SD) scenarios are simulated and as many moments as possible from the original distribution preserved. For the total freshwater resources from the external environment, four scenarios are developed for the three mass normal distribution

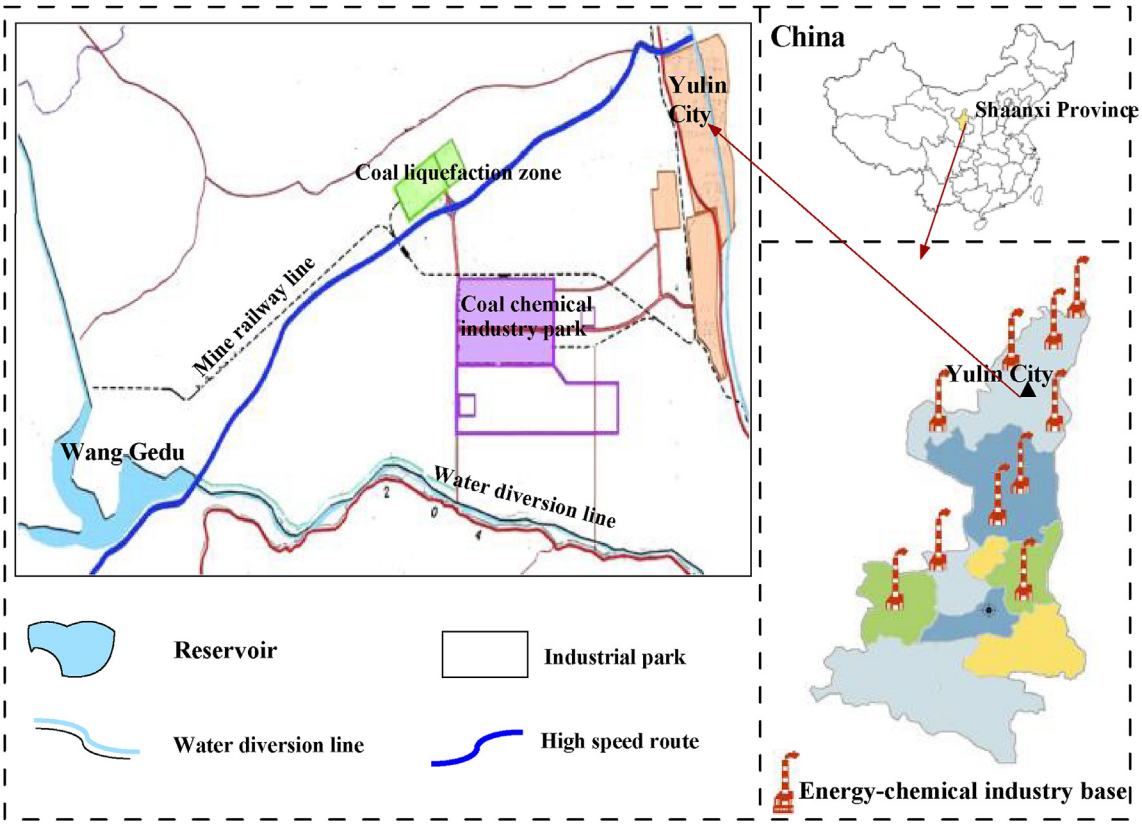

Fig. 2. Geographic location of Yuheng coal chemical industrial park.

Table 1
Basic data of the five coal chemical companies in Yuheng coal chemical park.

Company	Abbreviation	b_i	β_i^{loss}	WD_i^{min}	Project	PC_{ij}	UC_{ij}
(i)		(RMB/10^4 t)	(%)	(10^4 t/a)	(j)	(10^4 t)	(t/t)
China Coal Shaanxi Yulin Energy Chemical Co., Ltd.	Yanchang Petroleum	565.27	0.08	2739.92	Coal-to-Methanol(CTM)	225	12.94
					Methanol-to-Olefin(MTO)	70	11.2
					Methanol-to-Propylene (MTP)	70	11.2
Shaanxi Yanchang Petroleum (Group) Co., Ltd.	Yanchang Petroleum	326.56	0.12	245.56	Coal-to-Methanol(CTM)	100	12.94
					Coal based Acetic Acid(HAC)	160	11.2
					Coal-to-Oil (Synthetic oil) (CTL)	25	7.12
Shaanxi Yulin Excelle Coal Chemical Co., Ltd	Yulin Excelle	40.282	0.14	350.7	Coal-to-Methanol(CTM)	300	12.94
					Coal derived Aromatics(CTA)	100	279
					Coal-based PVC	60	10.5
Shaanxi Future Energy Chemical Corp	Future Energy	82.74	0.09	1147.3	Coal to Oil (indirect liquefaction) (CTL)	400	7.12

Table 2
Uncertain water resource parameter.

Scenario	Available freshwater resources $\tilde{Q}$ (10^8 m^3)			Probability p
	Low	Medium	High	
	($CV_1 = 0.12, \sigma_1 = 0.1528$)	($CV_2 = 0.18, \sigma_1 = 0.2831$)	($CV_3 = 0.25, \sigma_3 = 0.3182$)	
S_1	1.6294	1.9337	2.0157	0.045876
S_2	1.3862	1.4829	1.5089	0.454124
S_3	1.1595	1.0628	1.0367	0.454124
S_4	0.9163	0.6119	0.5300	0.045876

functions with equal expected values and different SDs. From the "Research Report for the Wang Gedu reservoir project in Shaanxi, Yulin", 0.12, 0.18, 0.25 are chosen as the CV values, with an expected value of $127.28 \times 10^6 m^3$ for $\tilde{Q}$. Accordingly, these three distributions correspond to a low, medium, and high level of variation. The specific scenarios and corresponding probabilities are shown in Table 2.

4.3. Results and discussion

In this section, optimization results under different decision maker attitudes for the confidence levels ($1-\alpha$) and the economic efficiency lose tolerance level (ε), and environmental conditions (i.e. water flow variation coefficient, CV) are given.

4.3.1. Scenario results

4.3.1.1. Scenario 1: CV = 0.12, ε = 0.40, and a changing 1-α. In this scenario, the risk-based optimization model is run under a stable water resources environment condition in which the water resources $\tilde{Q}$ has a variation level of CV = 0.12. The park authority attitude towards the CVaR constraint is set at 0.40 (ε = 0.40), indicating that the risk averse decision maker has a relatively high tolerance for economic efficiency losses in the park; that is, the highest level economic efficiency loss of 40%. By changing the confidence levels (1-α) in Eq. (2), a group of results were derived, as shown in Table 3. When 1-α = 0.99, the total pollution denoted by the comprehensive pollution equivalent value expressed in Eq. (1) is 5966.33 tonnes · yr^{-1}. It can be seen that the total pollution value increases noticeably with an increase in 1-α. From the results in this scenario, the total pollution produced by the whole park can be controlled within 5966.33 tonnes when the whole park economic efficiency loss is set at 40% or less under a low water resource variation.

4.3.1.2. Scenario 2: CV = 0.12, 1-α = 0.99, ε is changing. In this scenario, when the water resource is at a low variation level, the park authority has a 99% confidence interval. By changing the economic efficiency loss tolerance level, a group of results were derived that demonstrate the different decision maker attitudes towards the economic efficiency loss tolerance and the influence on the allocation strategies. From Table 4, it can be seen that total pollution increases if the decision maker expects a lower economic efficiency loss, which reflects the conflict between economic development and environmental protection. In the current resource conversion efficiency situation, to achieve greater economic returns, the park environmental damage cannot be controlled at a lower level. Under the low water resource variation environmental condition, the economic efficiency losses can be controlled at 0.1 with the maximum pollution being 8611.78 tonnes at a fixed confidence level of 1-α = 0.99. It is worth noting that the allocation results for the China Coal company are not sensitive to the changes inÅ; therefore, the other three companies can gain a larger share of the water and waste load allocations than when ε decrease to 0.20 to 0.40 with a step length of 0.05.

4.3.1.3. Scenario 3: CV = 0.18, ε = 0.40, 1-α is changing. In this scenario, the attitude towards the CVaR constraint is set at 0.40 (ε = 0.40), and the risk-based bi-level model is run under a moderate environmental condition with a medium variation in the water resource supply; that is CV = 0.18. By changing the confidence level (1-α), a group of results are determined, as shown in Table 5. In this scenario, if ε is set at 0.40, total pollution can be controlled to between 5772.15 and 6833.13 tonnes. As the results show, as the confidence level (1-α) increases from 0.80 to 0.99, the total pollution continues to grow, which indicates that a larger degree of risk aversion results in greater pollution, which obstructs the ecological objectives of the coal chemical industry. From the allocations to each company, it can be seen that Yanchang Petroleum and the Future Energy companies are allocated insensitive water and waste loads from the park authority, and that the allocations to the Yulin Excelle company increase when 1-α increases, indicating that the park authority intends to achieve a more accurate evaluation of the economic efficiency losses.

4.3.1.4. Scenario 4: CV = 0.18, 1-α = 0.99, ε is changing. Under a

Table 3
Optimal results under various confidence levels with CV = 0.12 and ε = 0.40.

Scenario indicators	Total pollution (tonne)	Allocated to Companies	Water allocations (10^4 m^3)	Allocated loads		Allocated to projects	Allocation results			Total costs
				COD (tonne)	NH^3-N (tonne)		Water (10^4 m^3)	COD load (tonne)	NH^3-N load (tonne)	(10^8 RMB)
(CV = 0.12, ε = 0.40, 1-α = 0.99)	5966.33	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.14
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	3768.79	1264.12	125.78	CTM	1941.00	731.51	72.79	92.77
						CTA	1098.23	413.89	41.18	
						PVC	315.00	118.72	11.81	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.12, ε = 0.40, 1-α = 0.95)	5722.98	China Coal	4441.50	1646.32	161.40	CTM	2652.75	1068.79	104.78	96.56
						MTO	784.00	315.87	30.97	
						MTP	649.43	261.66	25.65	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	3175.42	1065.09	105.98	CTM	1941.00	731.51	72.79	67.51
						CTA	560.00	211.05	21.00	
						PVC	325.12	122.53	12.19	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.12, ε = 0.40, 1-α = 0.90)	5578.91	China Coal	4081.09	1512.73	148.31	CTM	2652.75	1068.79	104.78	82.32
						MTO	709.85	286.00	28.04	
						MTP	392.00	157.94	15.48	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	3175.42	1065.09	105.98	CTM	1941.00	731.51	72.79	67.51
						CTA	560.00	211.05	21.00	
						PVC	325.12	122.53	12.19	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.12, ε = 0.40, 1-α = 0.80)	5406.18	China Coal	3648.99	1352.56	132.60	CTM	2573.07	1036.69	101.64	67.61
						MTO	392.00	157.94	15.48	
						MTP	392.00	157.94	15.48	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	3175.42	1065.09	105.68	CTM	1941.00	731.51	72.79	67.51
						CTA	560.00	211.05	21.00	
						PVC	325.12	122.53	12.19	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90

water supply condition where CV = 0.18 and a park authority confidence level of 99%, water and waste load allocation optimization is obtained, and a risk-averse park authority can reduce the economic efficiency losses to as low as possible. In this scenario, ε changes from 0.40 to a minimum constraint level with a step length of 0.05 until no optimal solution exists. From Table 6, the economic efficiency losses can be controlled at 0.30, with the maximum total pollution of 8112.53 tonnes being achieved when 1-α = 0.99 and CV = 0.18. It can be seen that a smaller ε leads to greater pollution in the park; that is, the lower the economic efficiency loss expected by the decision maker, the more difficult it is to control pollution. Therefore, the conflict between economic development and environmental protection are reflected mathematically in this scenario. The allocations for each company also have different sensitivities to the changes in the economic efficiency loss tolerance levels.

4.3.1.5. Scenario 5: CV= 0.25, ε = 0.40, 1-α is changing. In this scenario, it is assumed that the park authority has an optimistic attitude towards the economic efficiency losses; that is ε = 0.40,; and the water supply varies greatly; that is CV = 0.25. A set of solutions are obtained from the change of confidence intervals, as shown in Table 7. Comparing the results at the different confidence levels, it can be seen that the total pollution increases noticeably with an increase in 1-α. When the park authority has the highest risk aversion degree, the total pollution damage to the environment is 7072.08 tonnes, a rise of 1258.68 tonnes than at a confidence level of 80%, which proves that the attitude towards economic risk has a significant impact on water and waste load allocation strategies and the realization of environmental goals. The allocation results for each company indicate that not all companies are sensitive to the changes in 1-α. The China Coal and Future Energy companies, for example, are allocated a certain amount of water and waste load regardless of the changes in the confidence level; however, the Yulin Excelle company has increasing resource allocations and the Yanchang Petroleum company receives a sudden water and waste load resource increase when 1-α = 0.99. In conclusion, the sensitivity reactions at the four companies under the different resource consumption, pollutant emissions and production plans are not in complete accord.

4.3.1.6. Scenario 6: CV = 0.25, 1-α = 0.99, ε is changing. Under a very unstable water supply condition at CV = 0.25, by setting 1-α = 0.99, the optimization model is run to assess the sensitivity of the allocations strategy to a changing ε. In this scenario, with a change interval of 0.05, ε reduces from 0.40 until no optimal solution exists. From the results shown in Table 8, the economic efficiency losses

Table 4
Optimal results under different tolerance levels for economic return losses with CV = 0.12 and 1-α = 0.99.

Scenario indicators	Total pollution (tonne)	Allocated to Companies	Water allocations (10^4 m^3)	Allocated loads		Allocated to	Allocation results			Total costs (10^8 RMB)
				COD (tonne)	NH^3-N (tonne)	projects	Water (10^4 m^3)	COD load (tonne)	NH^3-N load (tonne)	
(CV = 0.12, 1-α = 0.99, ε = 0.35)	6370.68	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	4802.57	1610.87	160.29	CTM	3399.29	1281.11	127.47	84.48
						CTA	560.00	211.05	21.00	
						PVC	315.00	118.72	11.81	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.12, 1-α = 0.99, ε = 0.30)	6745.03	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	5836.36	1957.62	194.79	CTM	3882.00	1463.03	145.58	111.24
						CTA	997.36	375.88	37.40	
						PVC	315.00	118.72	11.81	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.12, 1-α = 0.99, ε = 0.25)	7139.20	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	2406.81	880.53	86.84	CTM	647.00	268.98	26.53	47.63
						HAC	1381.99	574.55	56.66	
						CTL	89.00	37.00	3.65	
		Yulin Excelle	6328.09	2122.56	211.20	CTM	3882.00	1463.03	145.58	133.95
						CTA	1120.00	422.10	42.00	
						PVC	630.00	237.43	23.63	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.12, 1-α = 0.99, ε = 0.20)	7551.36	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	3450.99	1262.55	124.51	CTM	1294.00	537.97	53.05	61.57
						HAC	1653.69	687.58	67.81	
						CTL	89.00	37.00	3.65	
		Yulin Excelle	6328.09	2122.56	211.20	CTM	3882.00	1463.03	145.58	133.95
						CTA	1120.00	422.10	42.00	
						PVC	630.00	237.43	23.63	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.12, 1-α = 0.99, ε = 0.15)	8611.78	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	3709.09	1356.98	133.82	CTM	1294.00	537.97	53.05	73.22
						HAC	1792.00	745.01	73.47	
						CTL	178.00	74.00	7.30	
		Yulin Excelle	6328.09	2122.56	211.20	CTM	3882.00	1463.03	145.58	133.95
						CTA	1120.00	422.10	42.00	
						PVC	630.00	237.43	23.63	
		Future Energy	2457.91	2784.69	297.03	CTL	2236.70	2784.69	297.03	59.90

can be controlled at 0.30 when CV = 0.25 and 1-α = 0.99, resulting in a total pollution load of 9006.49 tonnes. The allocation results for each company indicate that the China Coal and Yulin Excelle companies are allocated insensitive water and waste loads with changes in ε, and the Yanchang Petroleum and the Future Energy companies have different sensitivities to the changes in ε.

4.3.2. Comprehensive discussion

Based on the scenario analysis, a detailed discussion is given in this section.

Proposition 1. An equilibrium strategy is able to trade off the environmental and economic objectives

An IE approach gives guidance on reducing environmental damage while improving or sustaining economic performance (Alper, 1992). From the scenario results, total pollution and economic efficiency losses can be balanced with an emissions reduction. When the economic efficiency losses are below 15%, the total pollution produced by the park industrial companies can be controlled at 8611.78 tonnes. When ε increase, the total pollution shows a downward trend to a trough of 5966.33 tonnes when CV=0.12 and the confidence level is set at 0.99. In other words, if the economic efficiency is raised, there is a commensurate increase in pollutant emissions even if there are emissions reductions and water quality constraints. This result mathematically reflects the conflicts between the economic and environmental objectives in Eqs. (1) and (2). As shown in Tables 4, 6 and 8, integrating water use and pollution control can find equilibrium water resource and waste load strategies to achieve balanced efficient economic performance and control pollution damage to the environment under

Table 5
Optimal results under different confidence levels with CV = 0.18 and $\varepsilon = 0.40$.

Scenario indicators	Total pollution (tonne)	Allocated to Companies	Water allocations (10^4 m^3)	Allocated loads		Allocated to projects	Allocation results			Total costs (10^8 RMB)
				COD (tonne)	NH^3-N (tonne)		Water (10^4 m^3)	COD load (tonne)	NH^3-N load (tonne)	
(CV = 0.18, $\varepsilon = 0.40$, 1-$\alpha = 0.99$)	6833.13	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	6079.65	2039.23	202.91	CTM	3882.00	1463.03	145.58	122.14
						CTA	1120.00	422.10	42.00	
						PVC	408.89	154.10	15.33	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.18, $\varepsilon = 0.40$, 1-$\alpha = 0.95$)	6324.38	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	4674.71	1567.99	156.02	CTM	3285.50	1238.22	123.21	83.12
						CTA	560.00	211.05	21.00	
						PVC	325.12	118.72	11.81	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.18, $\varepsilon = 0.40$, 1-$\alpha = 0.90$)	6053.06	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	3825.47	1316.68	131.01	CTM	2618.67	986.91	98.20	75.11
						CTA	560.00	211.05	21.00	
						PVC	315.00	118.72	11.81	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.18, $\varepsilon = 0.40$, 1-$\alpha = 0.80$)	5772.15	China Coal	4451.92	1650.18	161.78	CTM	2652.75	1068.79	104.78	96.97
						MTO	784.00	315.87	30.97	
						MTP	659.02	265.52	26.03	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	3175.42	1065.09	105.68	CTM	1941.00	731.51	72.79	67.51
						CTA	560.00	211.05	21.00	
						PVC	325.12	122.53	12.19	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90

Table 6
Optimal results under different tolerance levels for economic return losses with CV = 0.18 and 1-$\alpha = 0.99$.

Scenario indicators	Total pollution (tonne)	Allocated to Companies	Water allocations (10^4 m^3)	Allocated loads		Allocated to projects	Allocation results			Total costs (10^8 RMB)
				COD (tonne)	NH^3-N (tonne)		Water (10^4 m^3)	COD load (tonne)	NH^3-N load (tonne)	
(CV = 0.18, 1-$\alpha = 0.99$, $\varepsilon = 0.35$)	7312.97	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	2847.05	1041.60	102.72	CTM	647.00	268.98	26.53	56.41
						HAC	1769.41	735.61	72.55	
						CTL	89.00	37.00	3.65	
		Yulin Excelle	6328.09	2122.56	211.20	CTM	3882.00	1463.03	145.58	133.95
						CTA	1120.00	422.10	42.00	
						PVC	630.00	237.43	23.63	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.18, 1-$\alpha = 0.99$, $\varepsilon = 0.30$)	8112.53	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	3709.09	1356.98	133.82	CTM	1294.00	537.97	53.05	73.22
						HAC	1792.00	745.01	73.47	
						CTL	178.00	74.00	7.30	
		Yulin Excelle	6328.09	2122.56	211.20	CTM	3882.00	1463.03	145.58	133.95
						CTA	1120.00	422.10	42.00	
						PVC	630.00	237.43	23.63	
		Future Energy	2051.88	2324.68	247.97	CTL	1867.21	2324.68	247.97	50.05

a certain scenario. In conclusion, the equilibrium strategies developed using the proposed model could help achieve the coordinated aims of reducing environmental stress and improving resource efficiency, as advocated by IE (Karn and Bauer, 2001).

Proposition 2. The application of IE encourages water resource recycling

Based on the IE principles, optimal water and waste load allocations were obtained under different scenarios for the four companies, as shown in Fig. 3. In scenario 1, 3, and 5, the China Coal and Yulin Excelle companies gained greater water resource allocations when the confidence interval increased. At the same time, the Future Energy company allocation was insensitive to changes in 1-α. The Yanchang Petroleum company was allocated 1859.31 104 of water under the scenarios except when 1-α=0.99 in scenario 5, when the highest water allocation of 2236.74 104 was given. a changing allocation trend can be seen, in that three companies except for the China Coal company are given a greater water allocation when the park authority expects a decrease in the economic efficiency loss risk. As ε reduces from 0.40 to a lower level with a step length of 0.05, the water allocated to all coal chemical companies increases under all examined water supply variation conditions. Therefore, from the scenario analyses, it can be concluded that when the park authority has a higher confidence and risk tolerance so that 1-α increases and ε decreases, the total water and waste load allocations increase because of the increase in internal water reuse rather than external water inflow, clearly demonstrating that the proposed method in this paper can encourage greater water recycling and increase overall park sustainability (Jia et al., 2016).

Proposition 3. Changes in the external environment affect objective realization and allocation strategies

Changes in rainfall impact the quality and quantity of the water supply. When the external environment changes, total pollution fluctuates and the economic efficiency losses can be controlled at different levels. The results from Supplementary Material shows how the environmental objective reflects the changes in CV, from which it can be seen that total pollution is sensitive to changes in water supply variability. In scenario 1, the total pollution is 5966.33 tonnes when the park authority has a high degree of confidence in the economic efficiency losses. When the water supply variation increases to 0.25, the total pollution grows by 18.53%, indicating that uncertain water resources makes it more difficult to control

Table 7
Optimal results under various confidence levels with CV = 0.25 and $\varepsilon = 0.40$.

Scenario indicators	Total pollution (tonne)	Allocated to Companies	Water allocations (10^4 m^3)	Allocated loads		Allocated to	Allocation results			Total costs (10^8 RMB)
				COD (tonne)	NH^3-N (tonne)	projects	Water (10^4 m^3)	COD load (tonne)	NH^3-N load (tonne)	
(CV = 0.25, ε = 0.40, 1-α = 0.99)	7072.08	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	2236.74	818.32	80.70	CTM	647.00	268.98	26.53	44.24
						HAC	1232.34	512.33	50.53	
						CTL	89.00	37.00	3.65	
		Yulin Excelle	6328.09	2122.56	211.20	CTM	3882.00	1463.03	145.58	133.95
						CTA	1120.00	422.10	42.00	
						PVC	630.00	237.43	23.63	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.25, ε = 0.40, 1-α = 0.95)	6486.37	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	5122.05	1718.03	170.95	CTM	3683.63	1388.27	138.14	87.90
						CTA	560.00	211.05	21.00	
						PVC	315.00	118.72	11.81	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.25, ε = 0.40, 1-α = 0.90)	6181.09	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	4279.02	1435.27	142.81	CTM	2933.33	1105.50	110.00	78.89
						CTA	560.00	211.05	21.00	
						PVC	315.00	118.72	11.81	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.25, ε = 0.40, 1-α = 0.80)	5813.40	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	1859.31	680.23	67.08	CTM	647.00	268.98	26.53	37.01
						HAC	896.00	372.50	36.74	
						CTL	93.19	38.74	3.82	
		Yulin Excelle	3263.64	1094.69	108.92	CTM	1941.00	731.51	72.79	71.71
						CTA	560.00	211.05	21.00	
						PVC	403.64	152.12	15.14	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90

Table 8
Optimal results under different tolerance levels for economic return losses with CV = 0.25 and 1-α = 0.99.

Scenario indicators	Total pollution (tonne)	Allocated to Companies	Water allocations (10^4 m^3)	Allocated loads		Allocated to projects	Allocation results			Total costs (10^8 RMB)
				COD (tonne)	NH^3-N (tonne)		Water (10^4 m^3)	COD load (tonne)	NH^3-N load (tonne)	
(CV = 0.25, 1-α = 0.99, ε = 0.35)	7581.67	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	3527.80	1290.65	127.28	CTM	1294.00	537.97	53.05	63.10
						HAC	1721.46	715.68	70.58	
						CTL	89.00	37.00	3.65	
		Yulin Excelle	6328.09	2122.56	211.20	CTM	3882.00	1463.03	145.58	133.95
						CTA	1120.00	422.10	42.00	
						PVC	630.00	237.43	23.63	
		Future Energy	1678.36	1901.50	202.83	CTL	1527.31	1901.50	202.83	40.90
(CV = 0.25, 1-α = 0.99, ε = 0.30)	9006.49	China Coal	4587.77	1700.54	166.72	CTM	2652.75	1068.79	104.78	102.34
						MTO	784.00	315.87	30.97	
						MTP	784.00	315.87	30.97	
		Yanchang Petroleum	3709.09	1356.98	133.82	CTM	1294.00	537.97	53.05	73.22
						HAC	1792.00	745.68	73.47	
						CTL	178.00	74.00	7.30	
		Yulin Excelle	6328.09	2122.56	211.20	CTM	3882.00	1463.03	145.58	133.95
						CTA	1120.00	422.10	42.00	
						PVC	630.00	237.43	23.63	
		Future Energy	2778.90	3148.36	335.83	CTL	2528.80	3148.36	335.83	67.72

total pollution. As shown in Tables 4, 6 and 8, the CVaR varies; under a lower water supply condition, the CVaR can be controlled within 0.15 to 0.40 with a change interval of 0.05; however, when the economic efficiency loss risk constraint reduces to a step length of 0.05, no optimal results can be achieved under medium or high water supply variation levels. Unstable water supply conditions not only influence the implementation of the total pollution requirement based on IE theory, but also exacerbate the risk of economic efficiency losses. From a comparison of the allocation results in scenarios 3, 5, 7, it can be seen that the water resource and waste load allocations at each company are sensitive to changes in CV; the specific sensitivities are shown in Fig. 3. Therefore, adapting industrial production to climate change affects resource and environmental management, which in turn leads to changes in industrial activities (Martin and Watson, 2016).

Proposition 4. Coal chemical companies are sensitive at varying degrees towards changes in the decision making environment

The allocation results in the different scenarios in Fig. 4,indicate the varying sensitivities at each company under different scenarios; as can be seen, each of the four companies have different sensitivities to changes in a parameter in the same scenario. For example, in scenario 1, the China Coal, Yanchang Petroleum and Yulin Excelle companies developed their coal chemical project production plans based on the water resource allocations from the park authority, which fluctuate as 1-α changes. However, the Future Energy company is able to develop their CTL production plans with a guaranteed water resource of 1527.31 10^4 m^3. In scenario 1, 3, and 5, the resource allocations increase with the growth in 1-α. In scenario 2, the Yulin Excelle company allocation increases; however, in scenarios 4 and 6, as ε decreases, the allocation does not change. From Fig. 5, the total costs (operating costs and environmental costs) partly change in the different scenarios. When the park authority has a higher confidence degree, in scenarios 1, 3, and 5, total costs increase for some companies but remain stable for others. Therefore, it can be concluded that when the park authority has tighter economic efficiency loss risk control, where ε is set lower and 1-α is set close to 1, this could lead to an increase in costs as the environmental costs grow. In summary, the coal chemical projects are planned based on the water resource allocations from the park authority and emitted pollutants to ensure water quality standards. Production plans based on the water resource and pollution emissions allocation were shown to be sensitive in different scenarios and had varying sensitivities to the changes, which was similar to the Knapsack problem (Sinha and Zoltners, 1979).

4.3.3. Management proposals

Based on the computation results and discussion for the Yuheng coal chemical park, some management proposals are given.

(1) Ecological concepts should be integrated to guide sustainable system development

Joseph Alper stated that “Industrial ecology enable industry to improve the efficiency of its process” (Alper, 1992). The application of IE principles and methods can promote the coordinated development of the economy and the environment (Karn and Bauer, 2001). Through the coupling of the industrial economic system and the ecological system, total water pollution and economic efficiency are highlighted as the major objectives in the proposed model in Eq. (5). As water quality and water pollutant reduction are set as the constraints, the proposed methodology is able to combine the controlled emission reductions while keeping the other pollutant emissions within environmental regulations. As discussed in Proposition 1 and Proposition 2, the integration of coal and water resource use and environmental protection through the strategic planning in the proposed methodology can achieve a balance between environmental protection and economic performance. Therefore, the IE principles should be applied to address sustainability and give insight into possible solutions.

(2) Coordinate conflicts through systematic management system collaboration

The IE has important principles for industry reformation that are gradually being embraced by leaders and policy-makers to address the inherent conflicts between economic growth and ecological environmental protection (Pauliuk et al., 2017). As the proposed methodology simultaneously considers the economic and

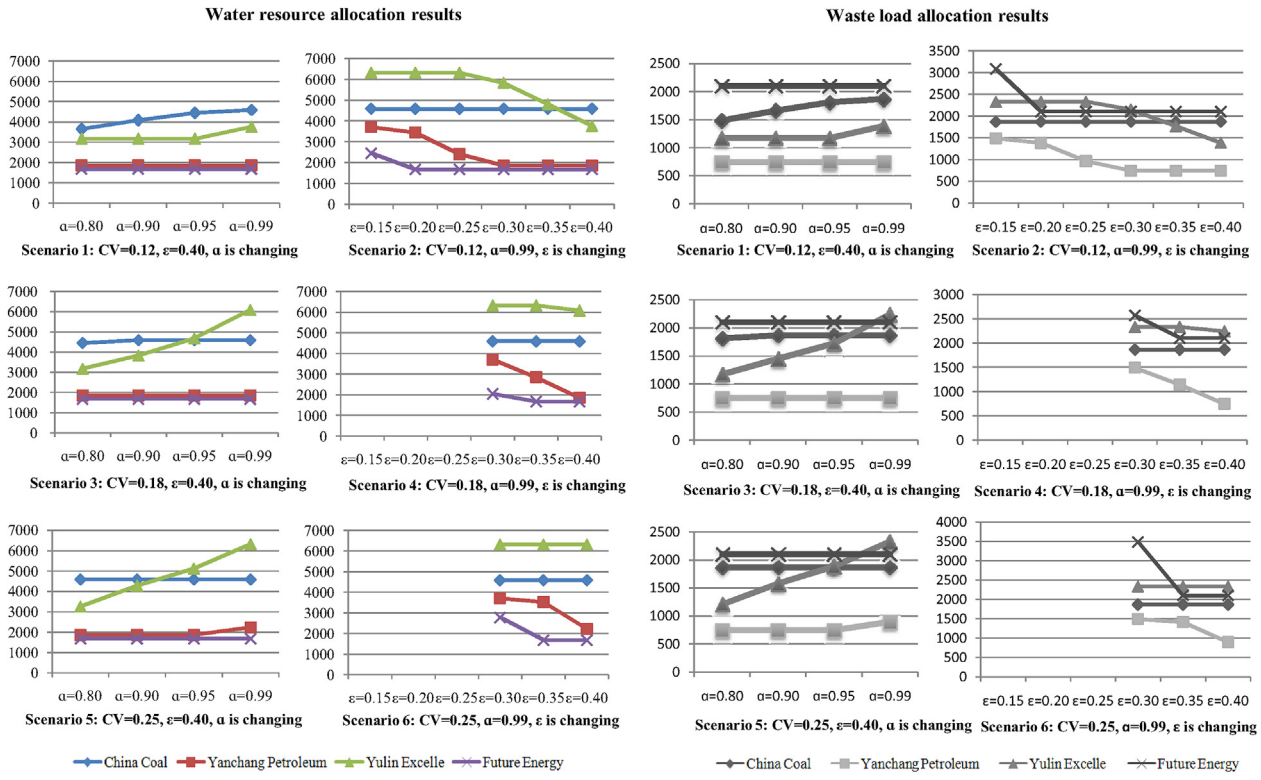
Water resource allocation results
Waste load allocation results
Scenario 1: CV=0.12, ε=0.40, α is changing
Scenario 2: CV=0.12, α=0.99, ε is changing
Scenario 3: CV=0.18, ε=0.40, α is changing
Scenario 4: CV=0.18, α=0.99, ε is changing
Scenario 5: CV=0.25, ε=0.40, α is changing
Scenario 6: CV=0.25, α=0.99, ε is changing
China Coal
Yanchang Petroleum
Yulin Excelle
Future Energy

Fig. 3. Water allocation results under different scenarios.

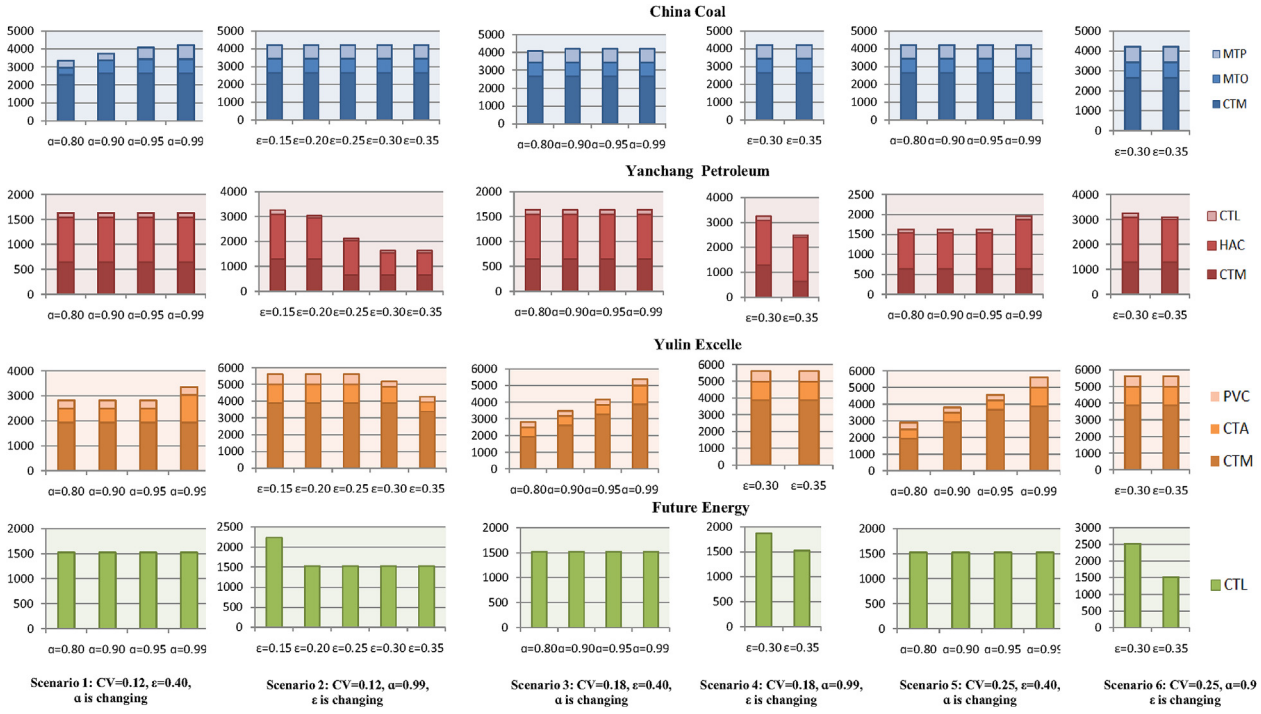

Fig. 4. Resource allocations to coal chemical projects under different scenarios.

environmental effects, the park authority and coal chemical companies can work together to achieve greater benefits than working alone. According to the results and the discussion in Proposition 3, there are trade-offs in this Stackelberg game between the park authority goals and the coal chemical stockholder' objectives. Therefore, it is more productive to integrate the skills and knowledge of the various decision makers to jointly resolve the conflicts. A system based on IE and the Stackelberg game allows for the clarification and reassignment of environmental responsibilities (for example, between the authority, the companies and the

Operation costs
Total costs
Environment costs
China Coal
Yanchang Petroleum
Yulin Excelle
Future Energy
α=0.80 α=0.90 α=0.95 α=0.99
Scenario 1: CV=0.12, ε=0.40, α is changing
ε=0.15 ε=0.20 ε=0.25 ε=0.30 ε=0.35
Scenario 2: CV=0.12, α=0.99, ε is changing
Scenario 3: CV=0.18, ε=0.40, α is changing
ε=0.30 ε=0.35
Scenario 4: CV=0.18, α=0.99, ε is changing
Scenario 5: CV=0.25, ε=0.40, α is changing
Scenario 6: CV=0.25, α=0.99, ε is changing

Fig. 5. Costs to each company under different scenarios (CNY). Note: the total costs and operating costs are on the left vertical axis; the environment costs are on the right vertical axis.

production projects), thereby reducing conflicts and promoting the design of equilibrium development strategies. There is an urgent need to establish a collaborative systematic system to coordinate the conflicts.

(3) Develop sensitive adaptation strategies that respond to environmental changes

As there are future uncertainties because of the inherent variabilities in the ecosystem, scenarios should be used to explore the potential consequences of the different response strategies (Xu and Li, 2012; Martin and Watson, 2016). As discussed in Proposition 3, he larger the variation in available water, the more the emissions and the larger the economic efficiency losses. Coal chemical production plans based on water and waste load allocations are sensitive to changes in the water environment, as discussed in Proposition 4. Changes in rainfall impact water resources with regard to quality and quantity, can reduce accessibility to suitable

water supplies, and increase water quality management problems. The scenario results conducted in subsection 4.3.1 provide valuable support for decision makers so they can adjust their practices to cope with climate change. The application of scenario analyses could address different uncertainties and help establish an effective link between possible climate change effects and decision maker responses; therefore, to guarantee sustainable development, it is necessary to develop sensitive adaptation strategies for possible future changes.

5. Conclusion and future study

In this study, a systematic decision making framework based on IE was developed to support efficient water utilization and pollution control in coal chemical industrial parks. In the proposed methodology, pollution damage and economic efficiency were systematically coordinated and the conflicting objectives of the park authority and the coal chemical companies on two levels were effectively quantified in trade-offs through a leader-follower Stackelberg game decision process. The results and discussion from the case study demonstrated that the economic efficiency performance and environmental pollutant damage can be balanced by equilibrium water resource and waste load allocation strategies. The application of IE has the potential to encourage water recycling in the park to reduce the risk of economic efficiency losses. By constructing a set of scenarios that measured the effects of the actual water supply conditions and the different decision maker' attitudes, sensitivity analyses were conducted and sensitive adaptation strategies provided to respond to various environmental and policy changes. With such a solution-based approach, the proposed model could be easily applied to industrial parks or zones facing water resource shortages and pollution control problems. These propositions and management proposals combined with the scenarios can assist decision makers involved in bi-level sequential decisions make adjustments to their control targets to make more informed decisions for overall sustainable IE development. In future research, the model could be improved to incorporate energy and water resource use to develop models for industrial ecosystems that include partnership exchanges inside industries or with other industries, and could also be extended to a systemic solution-driven approach towards sustainability that mitigates the effects of climate change.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2018.04.080.

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